

GRENADE RANGE MANAGEMENT USING LIME FOR DUAL ROLE OF METALS IMMOBILIZATION AND EXPLOSIVES TRANSFORMATION TREATABILITY

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1. ABSTRACT: The importance of live fire training for US forces cannot be overestimated. The success of our armed forces depends upon realistic training utilizing the actual weapons and munitions that will be used in theatre during strategic and tactical operations. However, a drawback of this type of realistic training is the potential contamination of firing ranges. Most munitions-contaminated soils found on training ranges contain a mixture of compounds. For hand grenade ranges (HGR), the prevalent munition used is the fragmentation grenade, typically composed of an iron shell and Composition B explosive material. Studies performed on ranges in both the United States and Canada have shown that there is a large degree of variability in munitions constituent type, concentration, size, and spatial distribution occurring on single ranges, as well as between different ranges. Contaminants present include explosive residue in the form of Composition B and Trinitrotoluene as well as metals such as zinc, iron, manganese, calcium, lead, chromium, copper, nickel, molybdenum, vanadium, and tin. The optimum treatment technology for successful remediation of distributed energetics and metals at training ranges should be inexpensive, easily applied in remote locations, effective on heterogeneous contaminant distributions, effective over large areas, effective on multiple compounds, be non-intrusive, to the extent possible, and able to be incorporated into normal range maintenance operations. Technologies currently available for the remediation of munitions-contaminated soil and groundwater do not meet these criteria. The objectives of this study were to evaluate and develop a cost effective management technology to control active grenade range contaminant mobility and promote on-site contaminant degradation.

2. TOXICOLOGY OF MUNITIONS RESIDUES: The concentrations of HE found by Jenkins et al. (2006) can pose significant health and environmental concerns. RDX is classified as a Class C carcinogen (possible human) based on research with mice (US EPA-IRIS, 1998a). TNT is considered to be mutagenic and carcinogenic, Class C (Agency for Toxic Substances and Disease Registry (ATSDR), 1995) and the US EPA has listed TNT as a priority pollutant (US EPA-IRIS, 1997). Major et al. (2002) reviewed the bioconcentration, bioaccumulation and biomagnification of TNT and RDX in the training range ecosystem. Plants accumulate TNT but the TNT is not biomagnified. Plants absorb RDX from the soil and surface/ground water and concentrate this contaminant in areas that are available for consumption (i.e., leaves and seeds). Major's research concluded that the potential for the biomagnification of RDX is high. Various metals are also deposited on the soil surface because of training exercises. These include zinc, manganese, and iron. Zinc is a contaminant at 986 of the 1,662 NPL sites (ATSDR 2005). The IARC lists zinc as Class D – not classifiable as to human carcinogenicity due to inadequate human exposure data. Zinc commonly binds to sediment and soil particles and does not transport easily into groundwater. When it does enter the water, it accumulates in fish and other organisms. Zinc does not accumulate in plants (US EPA-IRIS 2005). Small amounts of zinc are important to good health, but large doses are toxic and can lead to anemia and other changes in blood chemistry. There is no drinking water action standard established for zinc, but the reference dose is set at 0.3 mg Zn/kg body weight/day (US EPA 2004). Manganese is a trace element essential to human health in low doses. At high doses, it causes damage to the nervous system, liver and kidneys. Manganese is a contaminant at 603 of 1,467 NPL sites (ATSDR 2001). The IARC lists manganese as Class D – not classifiable as to human carcinogenicity due to inadequate human exposure data (US EPA-IRIS 1996). There is no drinking water action standard established for manganese, but the reference dose is set at 0.14 mg Mn/kg body weight/day (US EPA 2004). There is no tox data for iron and drinking water standards have not been established.

3. ENVIRONMENTAL FATE AND TRANSPORT: Brannon and Pennington (2002) have summarized the fate and transport processes for explosives in soil and water, providing descriptors for dissolution, adsorption coefficients, and transformation rates. Many of the munitions constituents occurring on training ranges have slow dissolution rates and low partition coefficients with a high potential for long-term contamination of ground and surface water (Brannon and Pennington 2002, Lynch 2002). The combination of a high, but reversible, sorption coefficient and the magnitude of contamination at many sites, results in a high potential for continuous percolation of contaminated water from surface and near-surface sources through the unsaturated zone to the groundwater.

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RDX has a low soil adsorption potential, which leads to a high potential of migration and contamination of groundwater. Jenkins et al. (2001) and Pennington et al. (2001, 2002) reported RDX-contaminated groundwater from several of the sites they tested, confirming the transport potential of energetics into groundwater. The fate of metals residues depends on the specific metals' physical and chemical properties and those of the soil. Metals occur in the form of discrete particles (intact munitions or fragments), as well as metal salts (weathering products) and dissolved metal or metallic complexes adsorbed to the soil matrix. Transport is likely when the metals are in a soluble form, for example, at low pH levels. Significant downward migration of metals from the soil surface can also occur when the metal retention capacity of the soil is overloaded. The capacity of soil to adsorb lead and zinc increases with increased pH levels. Controlling soil and pore water pH can, therefore, directly impact the fate and transport of metals associated with munitions residues.

4. CURRENT REMEDIATION TECHNOLOGIES: The optimum treatment technology for successful remediation of distributed energetics and metals contamination on training ranges should be inexpensive, easily applied in remote locations, effective on heterogeneous contaminant distributions, effective over large areas, effective on multiple compounds, be non-intrusive, to the extent possible, and able to be incorporated into normal range operations. Technologies currently available for the remediation of munitions-contaminated soil and groundwater have been reviewed by Stratta et al. (1998), the National Research Council (1999), Rodgers and Bunce (2001), Weeks et al. (2003), the United States Government Accountability Office (2005) and the Federal Remediation Technology Roundtable (FRTR), updated in 2006. Few remediation alternatives are available to treat soil and sediments and most of these involve ex situ treatment. Inherent in all ex-situ processes is the required excavation and transport of the contaminated soil with the associated health and safety risks. Also, ex situ systems are often part of a treatment train and, as such, are expensive to initiate and often produce residuals that also must be treated (Weeks et al. 2003). Therefore, an in situ technology is preferable. Two in-situ processes reviewed favorably by Rodgers and Bunce (2001) and the FRTR (2006) are enhanced bioremediation and phytoremediation. The length of time and the effects of climate on cleanup are disadvantages shared by these methods. In summary, no technology is currently available that can effectively remediate the HE contamination found on active training ranges or to prevent transport of these contaminants into the groundwater.

5. ALKALINE HYDROLYSIS: The use of the hydrolysis reaction as a means to degrade various environmental contaminants is reviewed in the U.S. Environmental Protection Agency (USEPA) report on Fate, Transport, and Transformation Test Guidelines (1998). The neutralization of HE by alkaline hydrolysis is presented by the National Research Council (1999) in their investigation of alternative technologies available to clean-up chemical weapons. To summarize the reaction, alkaline hydrolysis decomposes the explosive to organic and inorganic salts, soluble organic compounds, and various gases. There are vendors proposing the commercial use of base hydrolysis in an ex situ mode to remove explosive residues from scrap ordnance (Heaton 2001). Brooks et al. (2003) and Hansen et al. (2003) have investigated the removal of RDX from soil by alkaline hydrolysis. The efficiency of the alkaline hydrolysis reaction to remove explosive compounds from soil depends on bringing the explosive into direct contact with the hydroxide ion, which takes place within the soil pore water. The alkaline hydrolysis reaction worked well at removing nitroaromatics and nitramines from a variety of different soil types, although the reaction rate was slower in soils with high clay content (i.e., high cation exchange capacity, CEC). At pilot-scale, the reaction performed best when the lime was mixed well into the soil, bringing the hydroxide ion into close contact with the explosive material. Toxicity testing showed that the reaction reduced soil toxicity and mutagenicity. Amendments used to raise the pH in liquid and soil systems conventionally include metal oxides, hydroxides, and carbonates. These materials have been used in a variety of applications, including domestic and industrial wastewater treatment, acid mine drainage, and agricultural soil treatment. Several formulations of lime have been investigated for their ability to increase soil pH and degrade HE (Brooks et al., 2003). The calcitic lime, hydrated lime ($\text{Ca}(\text{OH})_2$), used primarily in engineering applications, proved most amenable to soil treatment for alkaline hydrolysis (Brooks et al. 2003). This application has now been used in field-scale studies (Thorne et al. 2004, Johnson et al. 2006, in press).

6. HYDROXIDE FATE AND TRANSPORT IN SOIL: Under topical applications of lime, the fate of hydroxide (OH^-) ions during transport through the soil will presumably be an important aspect of this proposed management technology. The alkaline hydrolysis reaction occurs in the aqueous phase. Therefore, the amendment (lime) and the munitions constituents must first dissolve into the soil pore water before the reaction can take place. Advective and dispersive processes will transport the hydrated lime cation (i.e. Ca^{2+}) and alkaline anionic species (i.e. OH^-). Cations will undergo ion exchange with other cations sorbed at exchange sites in the soil, including hydrogen (low pH soils) and aluminum (high clay soils). Reaction with H^+ exchanged from low pH soils inhibits the alkaline hydrolysis of the explosive munitions constituents by neutralizing the OH^- ions, effectively buffering the system. Base cations can also interact with the OH^- ions to form insoluble hydroxides, again removing them from potential

munitions constituent hydrolysis. Furthermore, hydrogen ions associated with various functional groups in humic matter may also dissociate under elevated pH conditions, and likewise inhibit alkaline hydrolysis of the explosive munitions constituents. Soil chemistry will, therefore, play an important role in energetics management through alkaline hydrolysis.

7. RANGE MANAGEMENT OF METALS AND EXPLOSIVES LADEN SOILS: Munitions residues are potential sources for soil and water contamination by heavy metals. The addition of lime is currently being used to treat heavy metals contamination in a variety of applications; wastewater treatment (Charerntanyarak (1999), Kurniawan et al. 2006), treatment of sewage sludge solids (Fang and Wong 1999, Wong and Selvam (2006) and soils (Mckinley et al. (2001, Geebelen et al. 2003, Gray et al. 2006). Kurniawan et al. (2006) reviewed several treatment techniques for treating wastewater contaminated with heavy metals. They found that lime precipitation was the most effective method to treat effluent with a metal concentration >1000 mg/L. The advantages of the lime treatment included the low capital cost and simplicity of operation. Charerntanyarak (1999), using Ca(OH)_2 as the precipitant, reported an optimum treatment pH of 11 and a removal efficiency of 99.3 to 99.8 percent for manganese, cadmium and zinc. Fang and Wong (1999) and Wong and Selvam (2006) investigated the use of lime in composting sewage sludge. The lime stabilized the heavy metals in the sludge (Cu, Mn, Zn, and Ni), significantly reducing the concentrations of water and acid-extractable metals. The lime amendment had no adverse side effects on the over-all system, as it did not slow compost maturation or interferes with seed germination. The authors recommended a lime addition of <1.0 percent (w/w). Highway construction projects have turned to contaminated soils (such as river silt and sewage sludge) to use as backfill material. Construction projects also use lime as a soil strengthener and conditioner. Mckinley et al. (2001) investigated the cementitious reaction that stabilizes the metals in the soil. They found that lead, arsenic, mercury, and iron concentrations were very low in the leachate from the treated soil. The authors suggested that metals complex with the soil organic matter in the silt and sludge. At high pH, the organic matter dissolves, leaving the metal in solution as a metal-organic complex. Although the leachate did not contain metals in concentrations high enough to be an environmental concern, the authors concluded that stabilization of contaminated soil using lime will perform best in soils with low organic matter content. Dermatas et al. (2003) added fly ash to contaminated soil in order to determine the effects on soil strength and heavy metals containment. Class C flyash contains at least 30% calcium oxide as well as silica, aluminum and iron oxides up to 50%, and is used primarily in construction and geotechnical applications. The authors concluded that the addition of fly ash increased the soil strength and enabled the containment of heavy metals. Lead and hexavalent chromium were immobilized and trivalent chromium immobilization was enhanced by fly ash addition to the soils. Geebelen et al. (2003) compared various bioassays to evaluate the success of soil lead immobilization treatments. Three amendments were evaluated: $\text{Ca(CO}_3\text{)}$, cyclonic ash and steel shot, and phosphate rock. The lead immobilization was tested using single and sequential extractions together with a microbiological sensor, a phytotoxicity test, plant uptake, and a Pb bioavailability test (PBET). Lime decreased the phytotoxicity and plant Pb uptake and passed the microbiological sensor. The authors did report that different amendments did not behave the same way in different soils with different sources of contamination. They suggested the use of a wide suite of indices to evaluate Pb availability after treatment. Field studies comparing red mud (high pH bauxite refining residue) and lime to remediate heavily contaminated soils found no difference in their performance (Gray et al. 2006). The authors reported a decrease in soluble and extractable metals concentrations in the treated soil. The amendments also reduced plant uptake of the metals as well as allowing re-vegetation of the soil. Munitions-related contamination, originally believed to primarily reside at production and handling facilities, is now known to include military training ranges and demolition test areas as well (Jenkins et al., 2001; Pennington et al., 2001, 2002). The sustainability of live fire ranges is of paramount importance to ensure continued training at army installations. Active military ranges are crucial to military readiness, and the development of effective treatment options for energetic and heavy metal contaminants is essential for range management and sustainability (Borthwick and Beshore, 2000; Jones et al., 2002). Alkaline hydrolysis has the potential to remediate both explosives and metals residues contaminating range soil. The research presented here examines basic aspects of lime application as a means of reducing the metals and explosives source zone contamination on live fire ranges.

8. EXPERIMENTAL DESIGN: Two separate lysimeter studies were conducted with the HGR soils. The first lysimeter study used native HGR soil from USMA and Fort Jackson. The USMA HGR soil mixed with hand grenade residue containing Composition B with a decreased volume of simulated rainfall was used for the second lysimeter study. In Lysimeter Study I (Table 1), eight lysimeters were loaded with HGR soil from USMA and Fort Jackson. One of the four lysimeters was a control with no addition of hydrated lime. The three other lysimeters had a lime dose equal to ½ times, 1 time, and 2 times the lime dosage requirement as determined by a modified ASTM method D6276-99a (ASTM, 1999). The lime dosage requirement was defined as the amount of lime necessary to bring the soil pH to above 11.5, a level that promoted alkaline hydrolysis of explosives (Davis et al. 2006, in press).

These lime dosages equated to 0.15%, 0.30%, and 0.60% lime for the native USMA soil and 0.5%, 1%, and 2% lime addition for the Fort Jackson soil for 1/2x, 1x, and 2x the respective lime dose required to elevate the pH above 11.5. On a weekly basis, RO water at a neutral pH was applied to each of the four lysimeter cells. The lysimeters were left uncovered after each weekly rain event. The USMA lysimeters were loaded with 210 kg of HGR soil while the Fort Jackson lysimeters were loaded with approximately 170 kg of HGR soil. Lysimeter Study II (Table 1) was conducted similarly to Lysimeter Study I except the total rainfall was reduced by 75% and the amount of lime added to the cells was increased. The reasons for the second lysimeter study were to reduce the potential flushing of the lysimeter cells and to observe the possible effects of different lime dosage amounts within the cells. Three lysimeters were loaded with 200 kg of crushed rock HGR soil from USMA. One of the three lysimeters was a control with no addition of hydrated lime. The other two lysimeters were dosed with 0.83% and 1.66% hydrated lime for 2x and 4x the respective lime dose required to elevate the pH above 11.5. On a weekly basis, RO water at a neutral pH was supplied to each of the three lysimeter cells and the lysimeters were left uncovered after each weekly rain event.

Table 1. Experimental Design for Lysimeter Study I and II.

| Lysimeter Cell | Project description | | | |
|---|-------------------------------------|---|------------------------------|--|
| | Study I | | Study II | |
| | % lime added to soil | Water Addition | % lime added to soil | Water Addition |
| 1 | USMA Control no lime | 2.94 inches (46.3 L) of RO water applied per week | USMA Control no lime | 0.734 inches (11.6 L) of RO water applied per week |
| 2 | USMA 0.150 % (0.315 kg total) | | USMA 0.83 % (1.745 kg total) | |
| 3 | USMA 0.300 % (0.630 kg total) | | USMA 1.66 % (3.490 kg total) | |
| 4 | USMA 0.600 % (1.260 kg total) | | | |
| 5 | Fort Jackson Control no lime | | | |
| 6 | Fort Jackson 0.5% (1.238 kg total) | | | |
| 7 | Fort Jackson 1.0% (2.476 kg total) | | | |
| 8 | Fort Jackson 2.0 % (4.951 kg total) | | | |
| ¹ The USMA Study I and II lime dose differ due to the different soil used to calculate the required lime dose. | | | | |

Explosives extractions, following SW 846 EPA Method 8330 (1994), were performed on the HGR soils before and after rain simulation tests were conducted. Soil core samples were collected from the lysimeters 8 and 16 weeks after lime addition and were analyzed for metals and explosives concentrations and soil pH.

9. OBJECTIVES: The objectives of this study were to evaluate and develop a management technology to control active grenade range contaminant mobility and promote contaminant degradation prior to field application (Davis et al. in publication). Column and lysimeter studies were performed using soil from active hand grenade ranges in order to demonstrate the potential of the lime application technology potential for reducing migration of RDX and metals from range soils. The following performance objectives for HGR management were monitored and evaluated during the lysimeter study:

- RDX in leachate: reduce RDX concentrations in waters leaching from the lysimeters by greater than 90% based on baseline and control area concentrations;

- RDX in surface water: reduce RDX concentrations in water running from the lysimeter by greater than 90% based on baseline and control area concentrations;
- Metals migration in pore water: Demonstrate no significant increase in metals concentration leaching from the lysimeter based on baseline and control area concentrations;
- Metals migration in surface water: Demonstrate no significant increase in metals migration in water running from the lysimeter based on baseline and control area concentrations;
- Assess the overall effectiveness and potential side effects of the lime amendment technology by maintaining the pH above 10.5 at the source area and below 9.5 outside the source area.

10. MATERIALS AND METHODS: This study was established in order to determine the appropriate protocols necessary to scale-up the technology of applying lime to soil from the lab to the field. This method was developed to both reduce metals migration and transform explosives on active hand grenade range soil. The field application will be used to manage munitions constituents on active training ranges. The treatability studies focused on several aspects of the scale-up and used HGR soils with different physical and operational properties. The studies focused on the application of lime, under controlled conditions, to soils that were laden with hand grenade explosives constituents in order to validate the transformation of explosives within limed soil, evaluate metals stability within limed soil, determine parameters, such as lime application and potential reapplication rates, for field sites, and develop application techniques to be used at operational HGRs. The HGR soils were subjected to column and lysimeter studies in order to understand and characterize the leachate and runoff waters generated from an equivalent amount of annual rainfall on the lime-treated soils.

11. SOIL COLLECTION AND PREPARATION: Soil samples were collected from the HGRs at Fort Jackson, S.C. and West Point (USMA), N.Y. The bulk samples that were used in the lysimeter treatability studies were transported to the ERDC-EL (Vicksburg, MS) in 55-gal, polyethylene-lined drums. In addition to the bulk drum samples, several grab and core samples were collected. Grab samples were collected using a small scoop and placed in plastic bags. Core samples were collected using a 2" internal diameter (ID) auger to a depth of 6 feet bgs and were placed into plastic bags for transport to the ERDC-EL. A composite sample of the contents of the drums was made using the following procedure. Air-dried soils were homogenized by hand in a large polyethylene-lined box using shovels, rakes, and a small hand tiller. Large rocks and organic debris were removed during the homogenization process. The soil was homogenized nine times. Based on earlier research (Tardy et al. 2004), this results in a standard deviation for the chemical analysis of ≤ 10 percent. Soil sub-samples were weighed and stored in 55-gal, polyethylene-lined drums before filling the lysimeters. Nine sub-samples of the newly mixed soil were taken for initial explosives and metals analysis. Representative aliquots of the soils were subjected to soil characterization that included soil pH, particle size distribution, TOC, and CEC. All tests were conducted in conjunction with control samples in order to obtain comparative results. Concurrent with this preliminary research, the USMA hand grenade range was reworked. A new top layer of crushed rock was put down after our initial soil characterization was conducted (i.e. the bottom soil at the USMA HGR still reflected the initial soil characterization conducted at ERDC-EL, but the top 12 to 18" layer of crushed rock did not).

13. pH COLUMN STUDY: A column study was conducted using the USMA crushed rock HGR soil in order to determine the effect passing through limed and then native soil would have on the leachate's pH. HGR soil (7.62 cm (3 inches) or 300 g) was mixed with 1.66 % (4x lime dose) hydrated lime (1.66gm lime per 100gm soil) and placed on top of 7.62 cm of native soil inside a 5.08 cm (2 inches) ID column. Two additional columns were packed with 15.24 cm of native soil and were set in series for a total soil depth of 45.72 cm. An equivalent of three years of rainfall (average of 47 inches per year) was passed through the columns and collected at the 15.24, 30.48, and 45.72 cm depths. As the leachate passed through the series of columns, the pH level of the leachate was determined after each 15.24 cm (6 inch) depth. Mesoscale Lysimeters: The mesoscale lysimeters were designed to allow for the collection of leachate flowing through the soil as well as runoff from the soil surface (Figure 1). The lysimeters were made from 1.905 cm (3/4-inch) thick, high-density polyethylene that measured 0.7874 cm (31 inches) by 0.7874 cm by 0.6096 cm (24 inches) (inside length \times width \times height). The lysimeters were placed on stands, constructed from angle iron, with a 0.0625 slope for collection of surface runoff water. Sufficient room remained above the soil mixture for a portion of the simulated rain to puddle and flow through the runoff trough into the runoff collection system. Leachate and runoff waters were collected in polyethylene pans. All tubing in the collection system was made from non-reactive silicon or polyethylene. Rainfall simulators were made from clear Plexiglas boxes and rested on mobile carts directly above the top of the lysimeters. A water reservoir containing RO water was placed on top of each rain simulator box. Air pressure regulators were fitted into the top of the simulators to control airflow and to apply air pressure to increase rainfall rates. A porous polyethylene material was secured to the bottom of the Plexiglas box using silicone adhesive caulk. This system generated a measured amount of

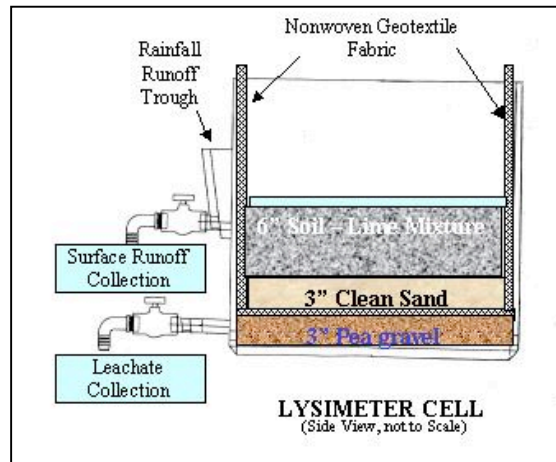


Figure 1. Cross section of lysimeter cell.

simulated rainfall amount was used that replicated the total average annual rainfall at Fort Jackson, S.C. and at West Point, N.Y. (47 inches per year). In order to simulate this amount of rainfall in 16 weeks, 2.94 inches per week or 46.3 kg of RO water was applied to each lysimeter. Approximately 45 minutes was required to apply the total amount of rainwater. The total volume of homogenized soil was divided into four sub-samples in order to provide the required soil mass for the lysimeters. The soil sub-samples were weighed and mixed in a rotary cement mixer for 15 min with the appropriate amount of hydrated lime. Three inches of pea gravel were placed on the bottom of the lysimeter to prevent the sediment from clogging the exit tubes during the weekly rainfall event. A layer of non-woven geotextile was placed on the pea gravel and draped around the inside of the lysimeter. A 15.24 cm (6 in) layer of coarse sand was placed on the geotextile, and the sand was compacted to three inches. On average, 200 kg of the HGR soil was then placed in three two-inch increments over the sand layer. The test soils were compacted to form a soil layer approximately six inches deep. Prior to conducting the tests, the lysimeter cells were saturated with RO water supplied from a 60-L polyethylene bottle. One end of a long piece of silicone tubing was attached to the dispensing outlet of the bottle, and the opposite end was connected to the leachate exit tube at the bottom of each lysimeter. Silicone tubing attached to an air pressure pump was fitted with a female quick-connect valve. A male quick-connect valve was placed in a large one-holed silicone stopper, and the stopper was placed in the top of the bottle. The bottle was then placed on a tall mobile stand and positioned over each lysimeter. Approximately 45 L of pressurized water was allowed to drain into each lysimeter in an upward flow through all of the lysimeter cell layers. After complete saturation occurred, as evidenced by a water layer on top of the soil mass, the excess water was drained from each lysimeter.

15. RESULTS AND CONCLUSIONS: In order to effectively manage metals and explosives on HGRs, an understanding is required of the geophysical processes and the mechanisms of explosives and metals transport at these sites. Metals and explosives releases from these impact areas occur through a variety of mechanisms, such as transport following soil erosion via rain and storm events. Explosives and metals can also be transported through leaching and surface water runoff. These mechanisms can result in soluble and particulate contaminant releases from impact areas. The objectives of this study were to evaluate and develop a management technology to control active grenade range contaminant mobility and promote on-site contaminant degradation. Hydrated lime was tested for its ability to transform explosives and stabilize metals in HGR soils collected from USMA (West Point, N.Y.) and Fort Jackson, S.C. Two lysimeter studies were conducted using the HGR soils with different lime applications. Lysimeter Study I used native HGR soils with an annual rainfall equivalent of 47 inches per year. Lysimeter Study II used HGR soil amended with hand grenade residue containing composition B, an annual rainfall equivalent of 11.75 inches per year, and an increased lime addition to the treated cells. The decreased rainfall amount in Lysimeter Study II was used primarily to reduce the washout effects associated with the larger rainfall volume of Lysimeter Study I. One goal of this research was to evaluate and develop a technology that could be used to manage munitions constituents on ranges by transforming or degrading explosives. Another goal was to use this same technology to permanently reduce the amount of total metals (dissolved and particulate) leaving the impact area. The results of this study indicate that hydrated lime amendment to hand grenade range soils was effective in achieving these goals. The results of this study indicate:

1. Reduced RDX leaving as leachate. RDX concentrations leaving the source area as leachate were reduced greater than 90% when the appropriate amount of lime was added.

2. Reduced RDX leaving as runoff. Mass of RDX leaving the source area in runoff was reduced greater than 90% when the appropriate amount of lime was added.
3. Stabilized metals in soil. The total metals leaving the source area as leachate were generally less than or not significantly greater than the metals leaving the control cell.
4. Stabilized metals on soil surface. The total metals leaving the source area as runoff were generally less than or not significantly greater than the metals leaving the control cell.
5. Effective treatment with minimal side effects. The soil pH was maintained within the treatment zone at greater than the desired 10.5, while surface and subsurface water pH leaving the source zone were controlled below the desired pH of 9.5 or established water quality criteria.

All of the treatment goals for the lysimeter study were met. Together, these results show that lime addition can be an effective range management treatment for munitions constituents on active ranges providing the military with an HGR that can withstand the realistic training while mitigating the mobility of munitions constituents such as HE and metals. In addition this method does not pose adverse side effects to the surrounding training area. The application of hydrated lime is a useful and cost effective technology to reduce explosives from leaving live fire ranges. Under experimental conditions, the alkaline hydrolysis degraded the explosives before they left the top 15 cm of treated HGR soils. Lime application as a range management technology is currently being demonstrated at the Fort Jackson, S.C. and USMA (West Point, N.Y.) HGRs. The field demonstration results from these ranges will be used to develop a guidance document on lime application for the dual role of metals immobilization and explosives transformation at active HGRs. As a result, U.S. military forces can continue to take advantage of large scale live fire training to support world wide operations, without significant environmental limitations imposed as a result of munitions use at ranges.

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